# Expanding the E in ESG with high-resolution global mapping of ecosystem services and corporate physical assets

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March 05, 2024

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**Abstract:**

Aligning economic activities with the global sustainable development agenda requires understanding companies' impacts on nature. Here, we present a new approach for quantifying the direct impacts of companies' physical assets on nature based on global maps for eight ecosystem services and biodiversity metrics. We apply this approach to a set of over 2,000 global, publicly traded companies with 580,000 mapped physical assets. We find that companies in utility, real estate, materials, and financial sectors have the largest impacts on average, but there is substantial variation among companies within all sectors. In addition, we use high-resolution satellite imagery to assess the impact of active lithium mines based on their footprints. We show that the impact varies substantially among mines and can also be tracked across time for a mine. This approach enables differentiation among companies and assets based on their impacts to nature relative to their revenue or production.

**Introduction**

Global acceleration of economic activity has raised many people's standard of living but is also disrupting the climate system, driving loss of biodiversity, and undermining Earth's life support systems[1]. These losses put global sustainable development goals, and the long-term societal prosperity that they underpin, at risk, as well as endanger key environmental agreements such as the Paris Climate Accords[2] and Kunming-Montreal Global Biodiversity Framework[3]. Consumers, investors, and regulatory bodies are increasingly calling for greater transparency around corporations' nature-related impacts to facilitate decisions that are in line with sustainable economic growth and development[4,5]. Meaningful change requires accessible, science-based information on corporate impacts to and dependencies on nature.

Demand for quantitative information on nature-related risks and opportunities is growing, driving important advances in measuring and reporting on companies' impacts and dependencies on nature. Efforts such as the Task Force on Nature-Related Financial Disclosures and the Science-Based Targets Network are advancing frameworks and guidance for tracking and reporting on nature-related impacts and dependencies[6,7]. Advances in methodologies, data, and tools for measuring impacts to nature are making quantitative reporting increasingly possible[8–10].

ESG (environmental, social, governance) approaches aim to evaluate companies on a range of sustainability- and ethics-related issues. To date, the focus of the environmental pillar of ESG has centered on greenhouse gas emissions, air pollution, water and waste management, and, more recently, impacts to biodiversity[11,12]. Existing approaches largely do not account for the ways corporate activities impact or rely on ecosystem services. Ecosystem services are the conditions or processes of ecosystems that help to generate benefits to people[13] including protection from natural hazards such as coastal flooding, water purification for clean water for drinking and recreation, and mental health benefits from enjoyment of nature. A broader representation of the multiple facets of corporate impacts on nature and its contributions to human well-being is critical to effectively managing nature-related risks and opportunities and to weighing tradeoffs between the benefits of economic activity and the potential harms to people and economies from the loss of nature.

Here, we leverage recent advances in high-resolution, global ecosystem service modeling[14,15] and the growing accessibility of high-resolution satellite imagery to develop a new, open-source approach for quantifying the direct impacts of physical assets on ecosystem services and biodiversity. Our approach scales from the level of individual assets to collections of assets, such as corporations or portfolios, using open-source, process-based ecosystem service models[14–16]. It overcomes limitations identified in existing solutions for accounting for companies' environmental impacts, including limited transparency in underlying models and metrics[17], limited ability to differentiate impacts within sectors[18], or reliance on regionalized values with low spatial resolution[18–20].

We demonstrate how our approach provides new, decision-relevant insights into corporate impacts on nature in two ways: First, we apply this asset-based approach to a diverse set of global companies across all sectors. Specifically, we evaluate the ecosystem services and biodiversity impacts of over 2,000 companies included in the MSCI ACWI index[21] – an equity index that spans large- and mid-cap companies from developed and emerging market countries – based on over 580,000 mapped physical assets[22] across all continents except Antarctica. Second, we use high-resolution satellite imagery to conduct a more detailed analysis of specific assets and show the added granularity and context that can be gained with asset-specific footprints. We focus on a set of active lithium mines with historical production data[22] because of the increasing demand for lithium in an energy transition[23,24], the physical nature of mining, and its environmental impacts[15,25,26]. We show how our approach can be used to differentiate impacts among assets of similar activity types (e.g., among different mines), and to track impacts over time.

**Results:**

## Global maps of impacts

To quantify the impacts of corporate physical assets, we first created new global maps for each of 4 ecosystem services and 4 biodiversity indicators under a scenario in which all land surface is returned to its potential natural vegetation. The 4 metrics of impacts to ecosystem services include: 1) reduced risk of flooding and erosion for coastal populations (coastal risk reduction), 2) reduced erosion and sediment trapping for improved water quality for downstream populations (sediment retention); 3) retention of nitrogen pollution for improved water quality for downstream populations (nitrogen retention); and 4) the number of people within 1 hour travel time able to access nature for potential recreation, cultural, and health benefits (nature access). The 4 biodiversity impact metrics include: 1) species richness of amphibians, birds, mammals, and reptiles (species richness), 2) habitat for threatened and endangered species (Red List species), 3) habitat for endemic species (endemic species), and 4) Key Biodiversity Areas (KBAs). See *Methods* for more details on the calculation of each metric. All metrics should be interpreted as indices with magnitudes that are meaningful to compare within a metric but not between metrics. Given the dominance of built infrastructure in the asset dataset (e.g., bank branches, retail stores, cell towers, power plants; Table S1), we assumed that the development of a physical asset resulted in the complete loss of ecosystem service or biodiversity values as compared to the retention of natural vegetation.

Our global analysis shows that ecosystem service levels vary greatly within regions and among services, with 0.5% of total land area (~700,000 $km^2$, similar to the area of Myanmar) falling in the $90^{th}$ percentile of values for 3 or more services (Figure 1a; Table S2). Coastal risk reduction services were, by definition, restricted to coastal areas and greatest in areas with large coastal populations. Areas of high sediment retention value are very geographically dispersed but highest near streams and rivers near populated areas. Nitrogen retention values are concentrated in India, China, Europe, the Midwest United States and East Africa, areas with high nitrogen loads from agriculture, high potential for natural vegetation to purify water, and especially high human populations with a need for clean water. Nature access is highest in and around urban areas, with notable hotspots in Europe, Asia, and the eastern United States, where high densities of people would benefit from access to natural areas.

Biodiversity values, on the other hand, have greater levels of overlap among the different metrics and a higher level of spatial concentration than ecosystem services, with 3.2% of total land area falling in the $90^{th}$ percentile for 3 or more biodiversity values (Figure 1b; Table S2). Biodiversity values are greatest in the tropics, and especially concentrated in the Amazon, Southeast Asia, the Guinean Forests of West Africa and the Eastern Afromontane region of East Africa, matching well-established hotspots of biodiversity[27].

These patterns point to the importance of high-resolution data to capture spatial variation in impacts to nature. The use of country or regional averages – an approach taken by some existing methods for accounting for environmental impacts[19,20,28] – risks substantially mis-classifying the degree of impact to ecosystem services or biodiversity from an asset or company. This is especially the case for ecosystem services, where values have high spatial heterogeneity, varying greatly over small distances.

In addition, the distinctive patterns across ecosystem services indicators as compared to biodiversity indicators (Fig. 1) shows that biodiversity values are not a good proxy for ecosystem services, and thus not sufficient for assessing nature-related impacts. Explicitly incorporating ecosystem services into assessments of corporate environmental impacts will be important to fully assess corporate impacts and the ability to address the nature-related impacts of companies on people.

**Variation in sector- and company-level impacts**

To quantify and compare company-level impacts, we used our global ecosystem service and biodiversity maps to assess 585,569 physical assets belonging to 2,173 companies in the MSCI ACWI index. In addition to accounting for differences in impact due to asset locations, we also accounted for differences in asset size by buffering asset locations by the median asset size by activity type (see *Methods/SI* for more details). This advances beyond the point locations (latitude/longitude) that are common to most corporate asset databases and allows us to account for the fact that, for example, between a mine and a cell tower in the same location, the mine will have more impact due to its greater footprint on the landscape. We evaluate companies' total impacts for each metric, as well as adjusted for total revenue. We omit nature access as an ecosystem service metric in this analysis because it primarily reflects how urban an asset is, which is not a relevant measure of impact when considering existing assets from the wide variety of sectors and companies evaluated here.

Companies in the utility, real estate, materials, and financial sectors have the largest total impacts per company on average (Figure 2). Utility companies tend to have high levels of impact across all ecosystem service and biodiversity metrics, both per company and relative to revenue. This is in part due to the large physical footprint of utility companies. Companies in the financial and real estate sectors have the highest impacts on coastal risk reduction. Their high area-adjusted impact on coastal risk reduction indicates that their assets tend to be in areas with high potential value for this service, specifically in or near densely populated coastal areas.

The large range in variation in impact among companies within a sector (Figure 2) points to the potential across sectors to identify companies with relatively high or low levels of ecosystem services or biodiversity impact. This allows decision makers to differentiate companies based on their production or revenue efficiency with regards to ecosystem service or biodiversity impacts. For example, someone looking to invest in a particular sector could choose to invest in those companies with relatively lower impact within that sector. Certain sectors and industries may depend more directly on ecosystem services, such as beverage companies within the consumer staples sector requiring reliable sources of clean water, and companies within the materials sector relying on timber for construction materials and paper products. However, a company in any sector may have substantial ecosystem service impacts. Therefore, these kinds of assessments should not be restricted to certain sectors, especially as data and tools become more accessible.

Our approach can also provide more detailed resolution within a sector at the industry level. For example, within the materials sector, one of the highest-impact sectors, there is substantial variation among industries on average but again high variation within industries (Figure 3). Metals and mining companies have the highest average impact, both in absolute and revenue-adjusted terms, across all metrics except coastal risk reduction. This is due to both the size and location of assets in this industry. As the impact per $km^2$ shows (Figure 3), metals and mining company assets are located in areas with particularly high values for red list species, overall species richness, and sediment retention services. In contrast, companies in the chemicals and containers and packaging industries have the lowest average impacts (Figure 3). Companies in these industries have, on average, a smaller footprint. Assets belonging to chemical companies tend to be in areas with lower values for coastal risk reduction and sediment retention impacts, as shown by the impact per $km^2$ (Figure3). Companies in both the chemicals and containers and packaging industries tend not to have assets near Key Biodiversity Areas. Again, even within a sector, our approach makes it possible to distinguish companies with relatively low impacts, either within the sector overall or within an industry. Taking these impacts into account during the investment process can help mitigate risk or minimize impacts of investments.

**Evaluating asset-level impacts: mining**

This approach can also be used for more detailed evaluations of impacts where assessments at the level of individual assets is desired and feasible. As an example, we analyze individual lithium mining assets. We integrated a dataset on the location of 23 global lithium mines with high-resolution (~5m) satellite imagery[29] to map the footprint of individual mines. We then combined these footprints with the global maps of ecosystem service and biodiversity values to calculate mine impacts. These impacts account for both mine location and the mine-specific area of land impacted.

Our results show that the magnitude of impact varies substantially among mines (Figure 4). The range of potential impacts of lithium mining on nature are determined by the location of Earth's lithium reserves relative to the location of ecosystem service and biodiversity hotspots, but even given this constraint, there are options for acquiring lithium with higher or lower costs to ecosystem services and biodiversity. This asset-specific information can be weighed alongside information such as differences in productivity and operation costs. Understanding the impacts of specific assets or project footprints on natural capital can help project developers, corporates, infrastructure investors, and other decision makers limit their negative impacts and optimize for production efficiency when evaluating investments in new or existing development.

Using high-resolution, asset-specific footprints also reveals the impacts of many lithium mines to be much higher than estimated by assuming a fixed, median size (Figure 4a). The fixed approach is generally able to differentiate between high- and low-impact mines for the ecosystem services of sediment retention and nitrogen retention but was not as effective at distinguishing differences for biodiversity (Figure 4b). Assuming a median area by asset type may be both necessary and sufficient when comparing across many assets, such as when comparing across thousands of companies. However, where feasible, asset-specific footprints provide valuable additional information and spatial precision in assessing impact, especially when comparing among assets within an activity type or analyzing an asset over time. Of the 23 lithium mines evaluated, the mine with the largest footprint (Chaerhan Lake, China at >3,250 $km^2$) is the most impactful mine on endemic species, Red List species, and species richness, but other mines had greater impacts on the other four measures. None impacted coastal risk reduction. Five different mines represent the highest impact mines across all seven metrics. Four of these five are in China, which contains 8 of the 23 total lithium mines assessed.

Our approach can also leverage high resolution, high frequency satellite imagery to assess how a mine's footprint – and associated impact – changes over time. Combining the mine footprint with high resolution ecosystem service and biodiversity maps is important because these impacts do not necessarily scale linearly with footprint area or production. Using the Greenbushes, Australia lithium mine as an example, with annual satellite imagery[29] and production data from 2016-2023[30], we find that the mine's total footprint increased around 75 percent, while annual production increased around 140 percent (Figure 5, Table S2). Impacts to nitrogen retention, sediment retention, and species richness each increased over 80 percent, slightly more than would be expected by the change in footprint size alone, indicating the mine expanded into higher impact areas over time. In contrast, impacts to nature access, habitat for endemic species, and habitat for threatened and endangered species increased slightly less than the increase in footprint size. Across all ecosystem service and biodiversity measures, the impact per tonne of lithium produced decreased between 2016 and 2023, apart from a period of low production around 2021 likely due to COVID-19. Given that demand for lithium is increasing and will likely continue to in a transition to a lower carbon economy[23,24], intensity metrics can help show which areas produce the most while limiting negative environmental impacts.

Capturing this level of granularity can help project developers and investors explore the impact of an asset over time and analyze whether a possible increase in negative impact due to a larger asset footprint is justified by a meaningful increase in production. In addition to evaluating past trends, the high-resolution ecosystem service and biodiversity impact maps could also contribute to implementation of the mitigation hierarchy at the asset level[31], enabling project developers to avoid and minimize impacts to the most sensitive locations. The ability to compare impacts among mines can help guide extraction towards more sustainable options for this important resource.

## Discussion

Our approach provides a science-based way to quantify the impacts of the footprint of physical assets on multiple ecosystem service and biodiversity metrics. This approach extends environment-related measures for ESG with ecosystem service metrics. It is scalable from assets to companies to portfolios, and across sectors, and thus can be used to inform a range of policy, corporate, and investor decisions. It is able to differentiate impacts based on assets' sizes and locations.

This approach accounts for the loss of ecosystem services and biodiversity attributable to the loss of nature directly from physical assets, similar to Scope 1 carbon emissions[32]. For some sectors, such as mining, these direct impacts may represent a substantial portion of a company's impact on nature. For other sectors, especially those with extensive supply chains, expanding the assessment to account for supply chain impacts will be critical to capturing the full extent of a company's impact. Here, there is great potential to integrate our approach with methods from supply chain analysis[33] and spatial Life Cycle Assessment (LCA)[19].

Further refinement of our approach could also allow for differentiation in impacts among and within activity types. For example, an agricultural field and a parking lot of equal size would have different impacts due to differences in the maintenance of vegetation, soil permeability, addition of fertilizers, and so forth. In addition, assets of the same type and size may differ in their use of best management practices or nature-based solutions, and thus differ in their impacts. Utilities and energy companies, for example, are often stewards of large land areas, and the management of ecosystems in and around solar facilities and power transmission lines can lead to substantial variation in impact and even the potential to create gains relative to current conditions[34,35]. These differences could be accounted for within our approach by adjusting the ecosystem service or biodiversity changes attributed to assets that employ certain sustainable practices.

Finally, the sustainability field would benefit from the development of common standards for defining baseline and impact scenarios so that assessments could attribute impacts in a robust, intercomparable way. Our approach currently uses potential natural vegetation as the baseline conditions. Some urban areas have been developed for many decades, if not centuries or millennia. Attributing full loss of nature at these sites to the current asset owner could disincentivize activities in existing urban areas and perversely incentivize new greenfield development. An alternative approach could consider urban areas fixed and focus on impacts outside historically developed areas[14], use sites' restoration potential as a reference scenario[36], or adjust impacts by the current population density surrounding the site, although each approach would come with its own methodological challenges and uncertainties.

We focus on accounting for impacts stemming from the loss of ecosystems, filling an important gap in existing sustainability and ESG approaches. Although accounting for pollution contributed directly by assets (e.g., fertilizer runoff from agriculture, mine tailings, the release of chemicals or air pollution) is beyond the scope of the current analysis, this would be a valuable future addition. Integrating estimates from existing LCA approaches of pollution generated by assets[19,37] with the spatially explicit modeling of impacts to people in our approach here could advance this aspect.

By using open-source models and drawing on the growing accessibility of asset location data and high-resolution satellite imagery, we were able to analyze the impacts of over 2,000 companies and nearly 600,000 assets without relying on company-reported information on ecosystem service and biodiversity impacts. This approach can provide corporate ESG metrics focused on impacts to nature with greater transparency and the potential for external verification. At the same time, data availability remains a challenge: asset-level data is available primarily for publicly traded companies, which represent only a fraction of corporate activities, and even for these companies, data is incomplete[38–40]. Satellite imagery can capture or be used to infer many important asset-level characteristics[41,42] and is continuing to drive advances in ecosystem service modeling at global and local levels[43]. Even so, these approaches cannot be expected to fully capture all impacts or values, and on-the-ground information will remain an important complement, especially for understanding local values. Ultimately, further improvements to the accessibility, completeness, and standardization of data will be important to extending these approaches to meet demand from consumers, investors, regulators, and companies themselves for high quality information on nature-related impacts.

## Methods:

### Global ecosystem service and biodiversity impact maps

We developed high resolution (0.0028 degrees, ˜300 meters) global maps for quantifying assets' impacts on 8 measures of ecosystem services and biodiversity. We first modeled potential natural vegetation, or the vegetation that might exist absent development in a given location, as the baseline condition. We followed the approach used by Damania et al.[14], applying to all land areas including current urban areas.

We then modeled the 8 measures of ecosystem services and biodiversity under these baseline conditions. We selected four ecosystem services for which global modeling was possible and which capture a range of values of nature that are produced and delivered through unique phenomena (e.g., hydrologic flows, coastal storms, human travel) such that they are not spatially redundant with each other, and which are not commonly captured by existing ESG approaches. These ecosystem services, sediment retention, nitrogen retention, coastal risk reduction, and nature access were modeled with the same methods as described in Chaplin-Kramer et al.[15], using extensions of the InVEST[16] suite of models. For nitrogen retention, we modeled loading rates based on the current land use/land cover[44], representing fertilizer application in agricultural areas and background loading rates for all other landcover types. Combing nitrogen loading from a current scenario with retention provided by a baseline scenario of potential natural vegetation allows us to estimate the nitrogen retention service that would be provided by returning a location to natural vegetation while keeping the rest of the landscape under current conditions. Again following Chaplin-Kramer et al.[15], for all ecosystem services biophysical measures were combined with measures of the number of people benefitting to yield a relative measure of realized ecosystem service value: number of people downstream benefiting from clean water from nutrient and sediment retention, number of people within the protective distance of coastal habitats for coastal risk, and number of people within 1 hour travel of natural and semi-natural lands for nature access.

We include four indicators of biodiversity, each capturing a different dimension. Species richness is the number of different vertebrate species (amphibians, birds, mammals, and reptiles) represented in an area. Red List species is a measure of the number of threatened, endangered, and critically endangered vertebrate species potentially present at a location according to the IUCN Red List of Species[45]. Endemic species are represented by a range-weighted species richness map, which weights rare species more heavily than common species. This is done by weighting each species by the inverse of its range size. Key Biodiversity Areas (KBAs) are areas that contribute significantly to the global persistence of biodiversity, identified according to a set of globally agreed-upon criteria[46]. Global maps of species richness, Red List species, and endemic species were modeled under baseline conditions (potential natural vegetation) following the methods in Damania et al. 2023[14]. We created a global map with binary values, indicating where locations were within 1 km of a KBA[47]. This was intended to account for the fact that development activities can impact sensitive biodiversity and ecological functions beyond a project's footprint, primarily within 1 km of distance[48,49].

To identify hotspots and their areas of overlap, we calculated the $90^{th}$ percentile of values for each ecosystem service or biodiversity metric. Oceans and areas with no data were excluded from the percentile calculations. Areas with positive values for coastal risk reduction and areas within 1 km of a KBA made up less than 10 percent of land area, so all non-zero values for these metrics are included in the hotspots.

### Quantifying company-level impacts

A company's impacts on ecosystem services and biodiversity will depend on its number of assets, the footprint size (area) of those assets, and their location relative to ecosystem service and biodiversity values on the landscape. Existing data on corporate assets may include an asset's location in terms of latitude and longitude, but often does not include information on the asset's footprint on the landscape. To estimate impacts across thousands of companies with hundreds of thousands of assets varying greatly in size, we estimated a median footprint size for each asset facility category in the S&P Physical Assets Database via random selection, visual detection, and measurement using GIS. The sampled assets' measurements were used to calculate median footprint sizes (areas or widths) for each category. These median values were then applied to each asset based on its category to create asset footprints. (See the Supplemental Information for more details.)

Focusing on a suite of assets that generally result in paved or bare ground and little vegetation (e.g., buildings, energy infrastructure, mines), we assumed that development of a corporate asset results in the complete loss of ecosystem services and biodiversity values estimated to exist under baseline conditions. To calculate the impact of each asset for each of the 8 ecosystem service and biodiversity metrics, we used zonal statistics[50] to calculate the total value under the asset footprint for each of the previously described global impact maps. We then summed asset-level impacts by company.

We applied this approach to the more than 2,000 companies within the MSCI ACWI index, using the S&P Physical Asset database[22] for information on each company's asset locations and category. We grouped companies by their GICS (Global Industry Classification Standard)[51] sector and industry to understand the differences among, and variation within, sectors and industries.

### Estimating detailed asset-level impacts

To quantify and compare impacts at the asset level within an asset's facility category, we identified active lithium mines with associated production data from the S&P Metals and Mining Dataset[30]. This resulted in a set of 23 mines. High resolution satellite imagery allowed us to map mine footprints and their change over time annually from 2016-2023. We calculated mine-level impacts for each year by summing the values of the previously described global impact maps under the footprint.

**Acknowledgements:** We thank Harun Dogo for his pivotal role in launching this collaboration, and Allison Bailey and Neil Nathan for their feedback and contributions to identifying data sources. The Morgan Stanley Institute for Sustainable Investing provided valuable input and framing. This work was funded by the Morgan

Stanley Institute for Sustainable Investing. LM was also supported by a grant from the Marianne and Marcus Wallenberg Foundation "Advancing the Research Frontier of Biosphere Stewardship, Strategic Research Collaboration and Postdoc Program between The Stockholm Resilience Centre, Stockholm University, and The Natural Capital Project, Stanford University."

**Data and code availability:** We provide the global ecosystem service layers under a CC BY 4.0 license at https://github.com/natcap/natural-capital-footprint-impact, along with code for quantifying impacts by asset type and company with user-provided asset and company data. All other databases and datasets used in this study derive from sources cited in the Methods section; associated licenses prevent us from redistributing the derived datasets.

**References cited:**

1. IPBES. *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services* . https://zenodo.org/record/3553579 (2019) doi:10.5281/zenodo.3553579.

2. Conference of the Parties to the United Nations Framework Convention on Climate Change. 7.d Paris Agreement. (2015).

3. Conference of the Parties to the Convention on Biological Diversity. 15/4. Kunming-Montreal Global Biodiversity Framework. (2022).

4. McKinsey & Company & Nielsen IQ. *Consumers Care about Sustainability—and Back It up with Their Wallets* . https://www.google.com/url?q=https://www.mckinsey.com/industries/consumer-packaged-goods/our-insights/consumers-care-about-sustainability-and-back-it-up-with-their-wallets&sa=D&source=docs&ust=1688750877223141&usg=AOvVaw0pk3JVzaxmX0-bYMUdpuHR (2023).

5. PwC. *Asset and Wealth Management Revolution 2022: Exponential Expectations for ESG* . www.pwc.com/awm-revolution-2022 (2022).

6. TNFD. *The TNFD Nature-Related Risk and Opportunity Management and Disclosure Framework Final Draft – Beta v0.4* . (2023).

7. SBTN. *Technical Guidance – Step 1: Assess* . (2023).

8. ENCORE. *ENCORE* https://encore.naturalcapital.finance/en.

9. WWF Biodiversity Risk Filter. https://riskfilter.org/biodiversity/home.

10. GLOBIO - Global biodiversity model for policy support - homepage | Global biodiversity model for policy support. https://www.globio.info/.

11. TFCD. *Guidance on Metrics, Targets, and Transition Plans* . (2021).

12. Pérez, L., Hunt, V., Samandari, H., Nuttall, R. & Biniek, K. Does ESG really matter—and why? *The McKinsey Quarterly* (2022).

13. Guerry, A. D. *et al.* Natural capital and ecosystem services informing decisions: From promise to practice. *Proceedings of the National Academy of Sciences* **112** , 7348–7355 (2015).

14. Damania, R. *et al. Nature's Frontiers: Achieving Sustainability, Efficiency, and Prosperity with Natural Capital* . (The World Bank, 2023). doi:10.1596/978-1-4648-1923-0.

15. Chaplin-Kramer, R. *et al.* Mapping the planet's critical natural assets. *Nat Ecol Evol* **7** , 51–61 (2023).

16. Natural Capital Project. InVEST. Stanford University, University of Minnesota, Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, Stockholm Resilience Centre and the Royal Swedish Academy of Sciences (2023).

17. Berg, F., Kölbel, J. F. & Rigobon, R. Aggregate Confusion: The Divergence of ESG Ratings*. *Review of Finance* **26** , 1315–1344 (2022).

18. Moran, D., Giljum, S., Kanemoto, K. & Godar, J. From Satellite to Supply Chain: New Approaches Connect Earth Observation to Economic Decisions. *One Earth* **3** , 5–8 (2020).

19. Chaplin-Kramer, R. *et al.* Life cycle assessment needs predictive spatial modelling for biodiversity and ecosystem services.*Nat Commun* **8** , 15065 (2017).

20. Patouillard, L. *et al.* Critical review and practical recommendations to integrate the spatial dimension into life cycle assessment. *Journal of Cleaner Production* **177** , 398–412 (2018).

21. MSCI. MSCI ACWI Index (USD) Index Factsheet. (2023).

22. S&P Global. S&P Global Market Intelligence. (2022).

23. Hund, K., Porta, D. L., Fabregas, T. P., Laing, T. & Drexhage, J.*Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition* . (2020).

24. IEA. *Net Zero by 2050 - A Roadmap for the Global Energy Sector* . (2021).

25. Giljum, S. *et al.* A pantropical assessment of deforestation caused by industrial mining. *Proc. Natl. Acad. Sci. U.S.A.***119** , e2118273119 (2022).

26. Luckeneder, S., Giljum, S., Schaffartzik, A., Maus, V. & Tost, M. Surge in global metal mining threatens vulnerable ecosystems.*Global Environmental Change* **69** , 102303 (2021).

27. Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B. & Kent, J. Biodiversity hotspots for conservation priorities.*Nature* **403** , 853–858 (2000).

28. International Energy Agency. *Emission Factors: Database Documentation (2022 Edition)* . https://www.iea.org/data-and-statistics/data-product/emissions-factors-2022 (2022).

29. Planet Labs PBC. 2016-2023 Planet Labs PBC global quarterly basemaps. (2023).

30. S&P Global. S&P Capital IQ Pro Metals and Mining. (2023).

31. Tallis, H., Kennedy, C. M., Ruckelshaus, M., Goldstein, J. & Kiesecker, J. M. Mitigation for one & all: An integrated framework for mitigation of development impacts on biodiversity and ecosystem services. *Environmental Impact Assessment Review* **55** , 21–34 (2015).

32. World Business Council for Sustainable Development & World Resources Institute. *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard, Revised Edition* . (2004).

33. Stadler, K. *et al.* EXIOBASE 3. Zenodo https://doi.org/10.5281/zenodo.5589597 (2021).

34. Walston, L. J. *et al.* Modeling the ecosystem services of native vegetation management practices at solar energy facilities in the Midwestern United States. *Ecosystem Services* **47** , 101227 (2021).

35. WWF & BCG. *Building a Nature-Positive Energy Transformation: Why a Low-Carbon Economy Is Better for People and Nature* . (2023).

36. Brancalion, P. H. S. *et al.* Global restoration opportunities in tropical rainforest landscapes. *Science Advances* **5** , eaav3223 (2019).

37. Farjana, S. H., Huda, N., Parvez Mahmud, M. A. & Saidur, R. A review on the impact of mining and mineral processing industries through life cycle assessment. *Journal of Cleaner Production***231** , 1200–1217 (2019).

38. Schlingemann, F. P. & Stulz, R. M. Have exchange-listed firms become less important for the economy? *Journal of Financial Economics* **143** , 927–958 (2022).

39. Murphy, A. America's Largest Private Companies 2022. *Forbes*https://www.forbes.com/lists/largest-private-companies/.

40. Maus, V. & Werner, T. T. Impacts for half of the world's mining areas are undocumented. *Nature* **625** , 26–29 (2024).

41. Nassar, R. *et al.* Quantifying CO2 Emissions From Individual Power Plants From Space. *Geophysical Research Letters***44** , 10,045-10,053 (2017).

42. Dethier, E. N. *et al.* A global rise in alluvial mining increases sediment load in tropical rivers. *Nature* **620** , 787–793 (2023).

43. Galaz García, C. *et al.* The future of ecosystem assessments is automation, collaboration, and artificial intelligence.*Environ. Res. Lett.* **18** , 011003 (2023).

44. European Space Agency. ESA CCI Land Cover. (2019).

45. IUCN. The IUCN Red List of Threatened Species. (2019).

46. IUCN. *A Global Standard for the Identification of Key Biodiversity Areas, Version 1.0* . https://portals.iucn.org/library/node/46259 (2016).

47. BirldLife International. Digital boundaries of Key Biodiversity Areas from the World Database of Key Biodiversity Areas. Developed by the KBA Partnership: BirdLife International, International Union for the Conservation of Nature, Amphibian Survival Alliance, Conservation International, Critical Ecosystem Partnership Fund, Global Environment Facility, Global Wildlife Conservation, NatureServe, Rainforest Trust, Royal Society for the Protection of Birds, Wildlife Conservation Society and World Wildlife Fund. (2019).

48. Chaplin-Kramer, R. *et al.* Degradation in carbon stocks near tropical forest edges. *Nat Commun* **6** , 10158 (2015).

49. Haddad, N. M. *et al.* Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances* **1** , e1500052 (2015).

50. Natural Capital Project. PyGeoprocessing. Stanford University, University of Minnesota, Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, Stockholm Resilience Centre and the Royal Swedish Academy of Sciences. (2023).

51. MSCI. GICS® - Global Industry Classification Standard. https://www.msci.com/our-solutions/indexes/gics.

**Figure 1. Global hotspots of impacts differ across ecosystem service and biodiversity metrics.** The eight maps on the right indicate the 10 percent of land area with the highest values for each of four ecosystem service metrics (top) and four biodiversity metrics (bottom). For coastal risk reduction and Key Biodiversity Areas, this includes all areas with values greater than zero. These individual metric maps were combined to create each of the two ecosystem service and biodiversity hotspot maps on the left, showing which land areas fall within the top 10 percent for one or more ecosystem service or biodiversity metrics.

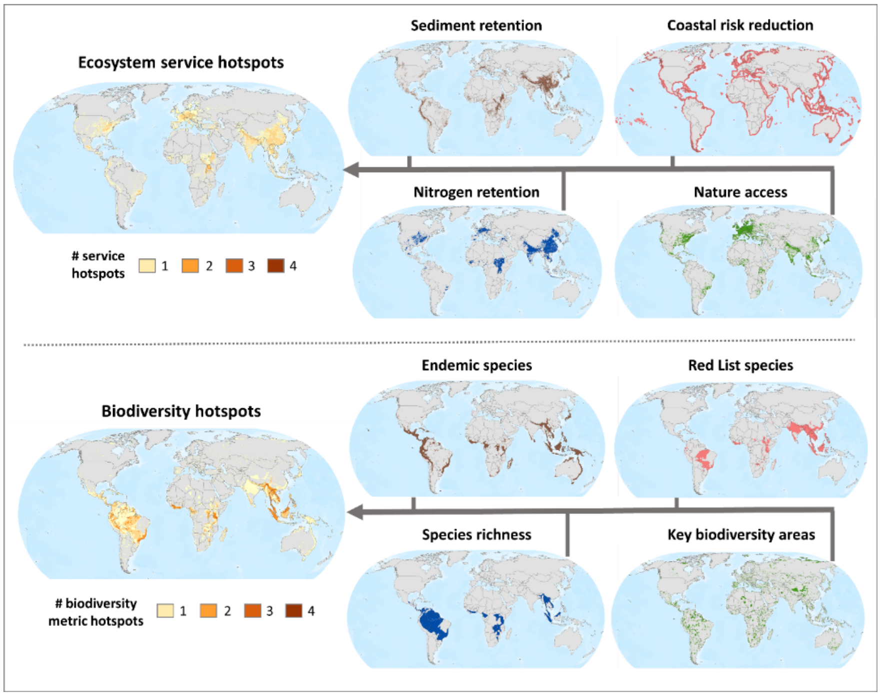
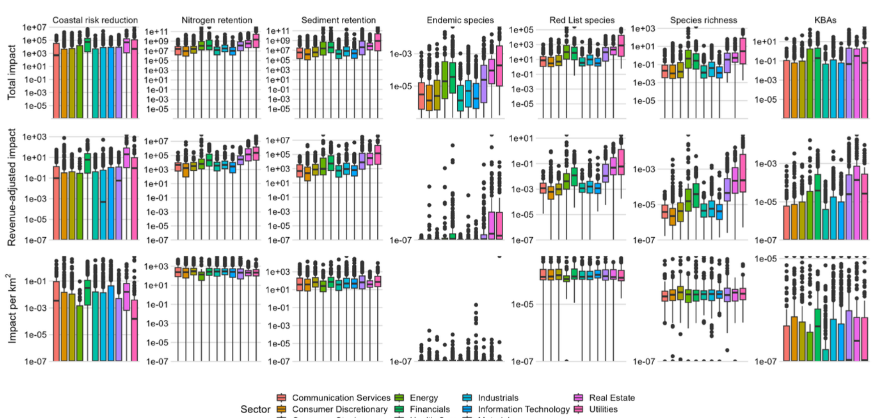
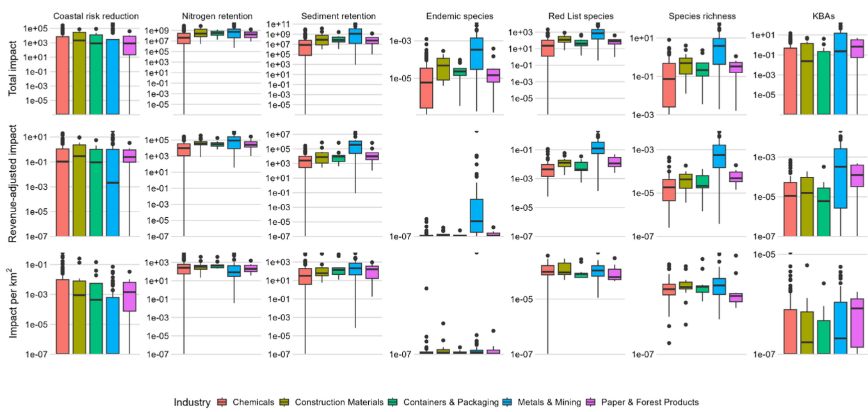



**Figure 2 . Company-level ecosystem service and biodiversity impacts vary across and within sectors.** Impacts are shown for three ecosystem service metrics (coastal risk reduction, nitrogen retention, sediment retention) and four biodiversity metrics (habitat for endemic species, habitat for threatened and endangered species, total species richness, and Key Biodiversity Areas). The top row shows the total impact per company, which is affected by the number, size, and location of each companies' physical assets. The middle row shows impact adjusted by company revenue. The bottom row shows total impact adjusted by the total area (km$^2$) of physical assets. A higher impact per km$^2$ indicates a company's assets are located in areas with great ecosystem service or biodiversity values. The values for each metric should be interpreted as indices; values are comparable within a metric but not between different metrics. For each boxplot, the midline indicates the median, with boxes extending from the 25th to 75th percentiles and whiskers extending to 1.5 times the interquartile range. Outliers beyond 1.5 times the interquartile range are indicated as dots. Note the log scale of y-axes.



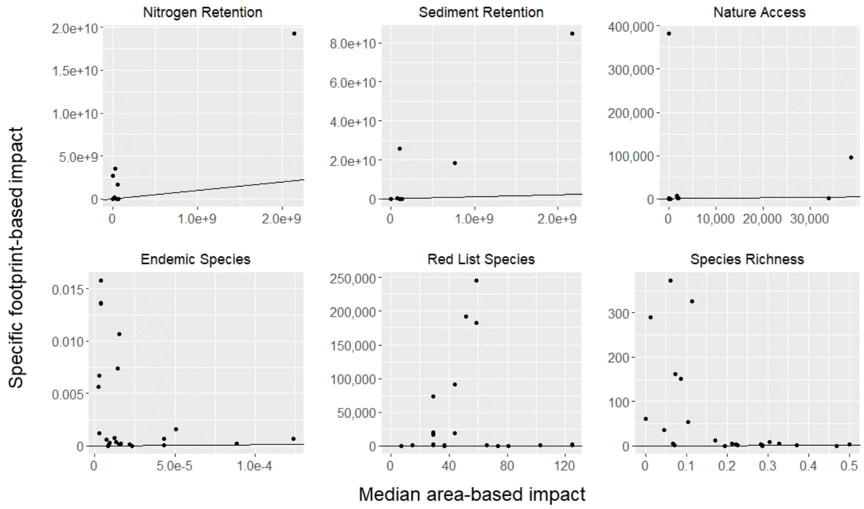
| Sector: | **Communica-tion Services** | **Consumer Discretionary** | **Consumer Staples** | **Energy** | **F** |
|---|---|---|---|---|---|
| No. companies | 113 | 234 | 169 | 70 | 33 |
| No. mapped assets | 9,449 | 69,160 | 31,519 | 17,205 | 20 |
| Footprint area (km$^2$) | 5.04E+07 | 2.67E+08 | 1.78E+08 | 6.83E+09 | 5. |

**Figure 3. Within the materials sector, company impacts vary across and within industries.** Impacts are shown for three ecosystem service metrics (coastal risk reduction, nitrogen retention, sediment retention) and four biodiversity metrics (habitat for endemic species, habitat for threatened and endangered species, total species richness, and Key Biodiversity Areas). The values for each metric should be interpreted as indices; values are comparable within a metric but not between different metrics. For each boxplot, the midline indicates the median, with boxes extending from the 25th to 75th percentiles and whiskers extending to 1.5 times the interquartile range. Outliers beyond 1.5 times the interquartile range are indicated as dots. Note the log scale of y-axes. The top row shows the total impact, which is affected by the number, size, and location of each companies' physical assets. The middle row shows impact adjusted by company revenue. The bottom row shows total impact adjusted by the total area (km$^2$) of physical assets. A higher impact per km2 indicates a company's assets are located in areas with great ecosystem service or biodiversity values.

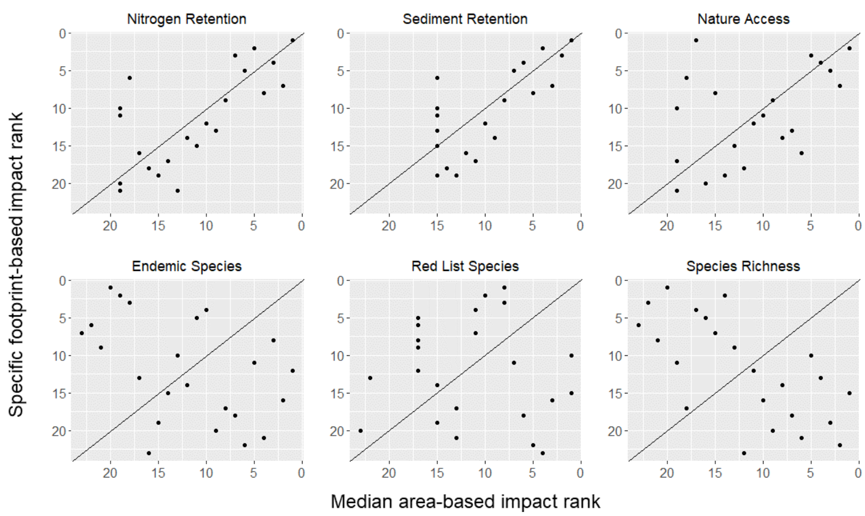



| Industry: | **Chemicals** | **Construction Materials** | **Containers & Packaging** | **Metals & Mining** | **Pa** |
|---|---|---|---|---|---|
| No. companies | 102 | 16 | 13 | 75 | 10 |
| No. assets | 3,436 | 1,249 | 620 | 3,407 | 337 |
| Footprint area (km$^2$) | 1.09E+08 | 3.30E+07 | 1.73E+07 | 1.34E+09 | 1.4 |

**Figure 4. Both mine size and location are important drivers of variation in estimated impacts.** The estimated impact of 23 lithium mines is based on high-resolution, mine-specific footprints is shown on the y-axis, compared to the estimated impact using median mine area on the x-axis. Panel a compares estimates of total impact, while panel b compares ranks. A rank of 1 corresponds to the greatest impact for a given metric. The 1:1 line is shown in black. Using the median mine area substantially underestimates the impacts of the highest impact mines as compared to using a mine specific-footprint. Comparing ranked impacts (b), the median area-based approach differentiates higher and lower impact mines for nitrogen retention, sediment retention and nature access, but not for endemic species, Red List species, or species richness. No mines were located in coastal areas or near Key Biodiversity Areas, so coastal risk reduction and KBA metrics were omitted.



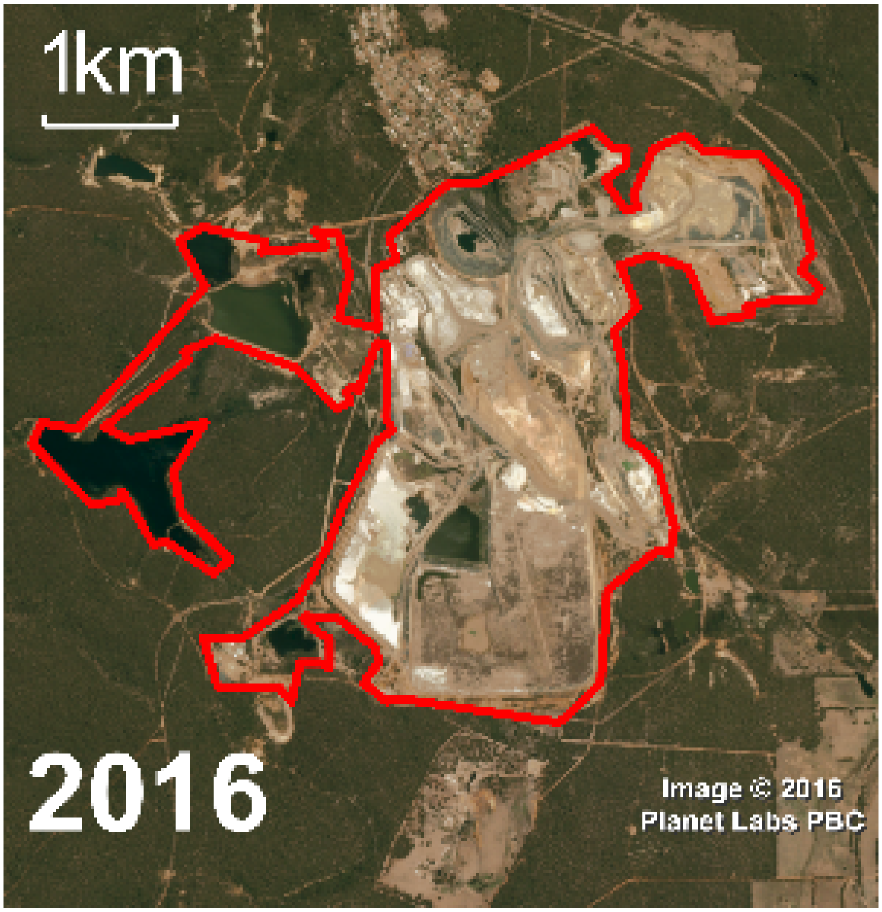

a)

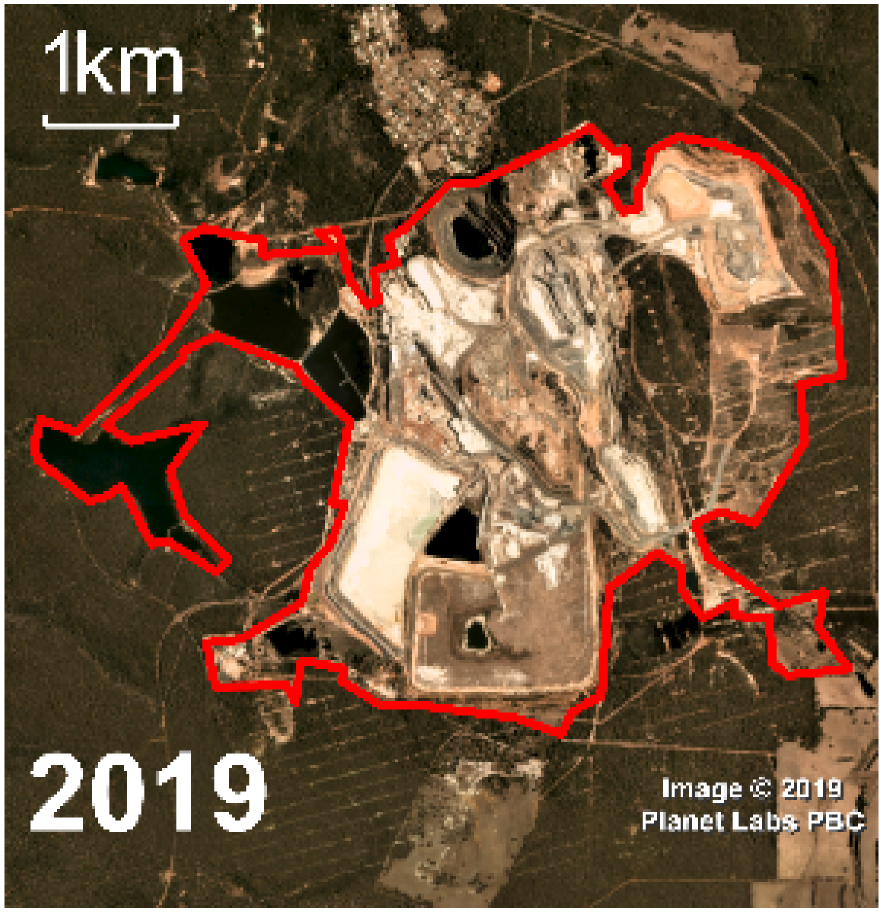


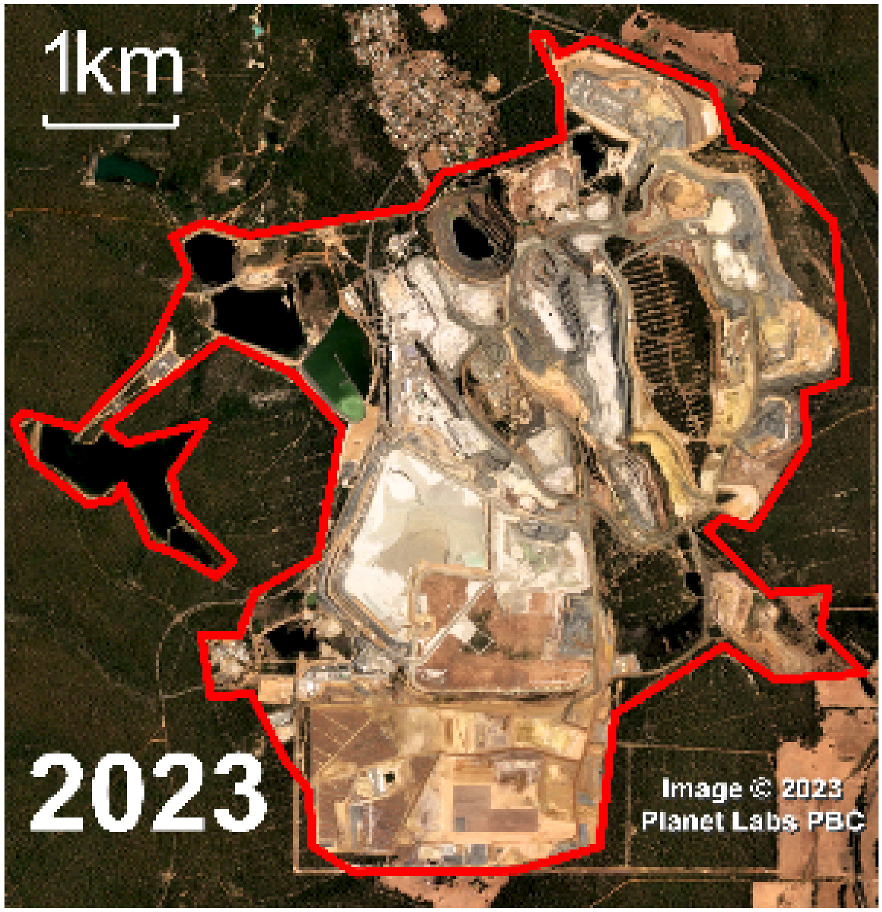

b)

**Figure 5. Patterns of change in mine impact vary over time and among ecosystem service and biodiversity metrics.** Panel a shows the footprint of the Greenbushes, Australia lithium mine mapped from satellite imagery across three time periods (2016, 2019, and 2023). Panel b shows the change in mine impact over time relative to 2016 in terms of total impact, impact per tonne lithium produced, and impact per km2 of mine footprint. Values for impacts to coastal risk reduction and Key Biodiversity Areas (KBAs) are zero across all years, and so these metrics are not shown.

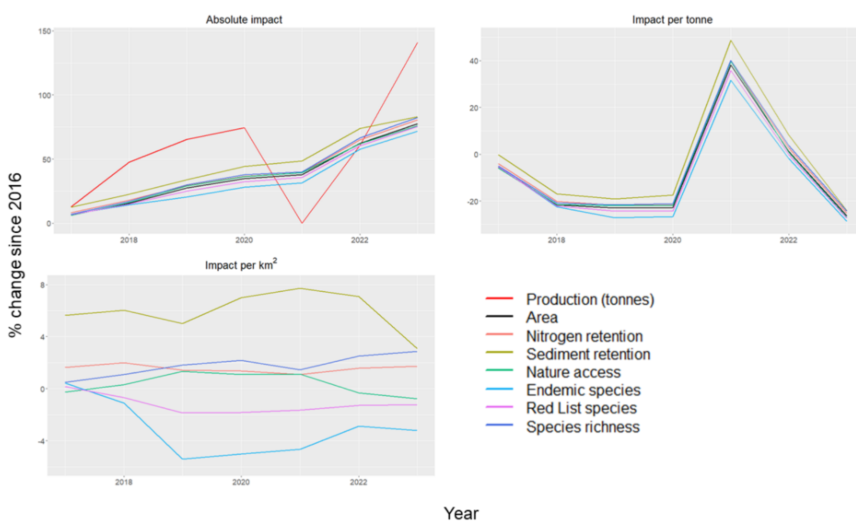
a)


1km
2016
Image © 2016
Planet Labs PBC


1km
2019
Image © 2019
Planet Labs PBC




b)




**Supplemental Information:**

**Quantifying company-level impacts – calculation of median footprint sizes by facility category:**

We estimated a median footprint size for each asset facility category in the S&P Physical Assets Database. For each category, asset locations were randomly selected for measurement in GIS. If a selected asset's presence was visually detected and verified with high-resolution satellite imagery, its physical footprint was traced and measured. For all but two facility categories, areas were measured. The two remaining categories ("transmission line" and "natural gas pipeline") were linear, thus their assets' widths were measured instead. Between two and 46 assets were sampled for each facility category. The sampled assets' measurements were used to calculate median footprint sizes (areas or widths) for each category.

For non-linear assets, the point location or each asset was buffered to create a circle of the appropriate area for its category.

For the linear assets, a minimum spanning tree approach was used to connect multiple point locations by unique asset number. Then, the calculated median width was applied to create footprints.

**Table S1.** Number of assets per S&P Physical Assets Database facility category in analysis. Assets within facility categories may fall under multiple sectors, as sectors are assigned the company level based on a company's principal business activity.

| **Facility category** | **Assets** |
|---|---|
| Bank Branch | 183,116 |
| Cell Tower | 176,298 |
| Retail Store | 98,423 |
| Instn Address | 23,550 |
| Company Headquarters | 20,908 |
| Regulated Sites | 17,779 |
| Gas Receipt/Delivery Points | 16,901 |
| Power Plant | 14,044 |
| Transmission Line | 6,608 |
| Multifamily | 3,295 |
| Multi-Use | 2,803 |
| Mining Property | 2,370 |
| Data Center | 2,332 |
| Office | 1,951 |
| Warehouse/ Distribution Center | 1,809 |
| Shopping Center | 1,682 |
| Assisted Living | 1,468 |
| Residential | 1,415 |
| Self-Storage | 1,350 |
| Medical Office | 1,127 |
| Manufactured Home | 1,036 |
| Other Retail | 846 |
| Regional Mall | 819 |
| Industrial | 645 |
| Natural Gas Pipeline | 535 |
| Full-Service Hotel | 409 |
| R&D Facility | 358 |
| Single Tenant | 334 |
| Health Care | 324 |
| Skilled Nursing | 302 |
| Single Family | 292 |
| Coal Mine | 279 |
| Independent Living | 232 |
| Inpatient | 230 |

| | |
|---|---|
| Gas Storage Facility | 218 |
| Limited-Service Hotel | 213 |
| Specialty | 205 |
| Hotel | 194 |
| Budget Hotel | 176 |
| Outlet Center | 170 |
| Land | 120 |
| Office Parks | 107 |
| Power Center | 81 |
| TV | 69 |
| Restaurant | 69 |
| Casino | 61 |
| Manufacturing | 59 |
| Student Housing | 50 |
| Rehabilitation | 48 |
| Parking Facility | 47 |
| LNG Facility | 38 |
| Dockside Casino | 31 |
| Industrial Park | 29 |
| Continuing Care Retirement | 26 |
| Recreation | 22 |
| Outpatient | 22 |
| Timber | 18 |
| Extended Stay Hotel | 18 |
| Cold Storage Unit | 16 |
| Track-Affiliated Casino | 12 |
| Golf Course | 10 |
| Flex/ Service Center | 10 |
| Cineplex Theater | 5 |
| Health Club | 4 |
| Psychiatric | 3 |
| AM | 3 |
| FM | 2 |
| Cruise Ship Casino | 2 |
| Car Dealership | 1 |
| Bowling Alley | 1 |

**Table S2. The global area covered by the ecosystem service and biodiversity hotspots shown in Figure 1,** given as both total coverage area and percent of the total land area included in the analysis.

| Number of ecosystem service hotspots | Hotspot area ($km^2$) | Percent of total land area |
|---|---|---|
| 1 | 18,684,090 | 13.9 |
| 2 | 6,971,635 | 5.2 |
| 3 | 694,236 | 0.5 |
| 4 | 27 | 0.00002 |

| Number of biodiversity hotspots | Hotspot area ($km^2$) | Percent of total land area |
|---|---|---|
| 1 | 22,281,812 | 16.5 |
| 2 | 8,434,036 | 6.3 |

| Number of biodiversity hotspots | Hotspot area ($km^2$) | Percent of total land area |
|---|---|---|
| 3 | 3,828,870 | 2.8 |
| 4 | 534,993 | 0.4 |

**Table S3.**

| Metric | % absolute change | % change intensity |
|---|---|---|
| footprint area | +77.4 | -26.4 |
| production | +141.0 | NA |
| nitrogen retention | +80.5 | -25.1 |
| sediment retention | +82.9 | -24.1 |
| nature access | +76.1 | -26.9 |
| endemic species | +71.8 | -28.7 |
| Red List species | +75.3 | -27.3 |
| species richness | +82.5 | -24.2 |